REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
10-10-00

3. REPORT TYPE AND DATES COVERED
Final Technical 6-1-97/5-31-00

4. TITLE AND SUBTITLE
A Coupled Physical-Biological Model of the North Indian Ocean

5. FUNDING NUMBERS
N00014-97-1-0766

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
University of Colorado/CCAR
CB 431
Boulder, CO 80309

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
ONR-Seattle

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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20001018 008

14. SUBJECT TERMS

15. NUMBER OF PAGES
35

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Uncl.	Uncl.	Uncl.	

Final Report

A Coupled Physical-Biological Model of the North Indian Ocean (N00014-97-1-0766)

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Under support from

AASERT Program
Office of Naval Research

Abstract

The principal objective of this study was to formulate a realistic coupled physical-biological model of the upper ocean and apply it to the North Indian Ocean. This meant that the physical model must conform as close as possible to reality and the biochemical model must incorporate recent findings from programs such as JGOFS. We have been able to formulate a state-of-the-art coupled physical-biological model and test it in 1-D mode against available data sets (Kantha, 2000). We have also been able to set up a 3-D data-assimilative circulation model of the North Indian Ocean and estimate the physical state of the upper ocean there during 1993-1999 (Lopez and Kantha, 2000 a and b).

Introduction

The motivation for this study arises from the fact that the North Indian Ocean is unique in being affected by seasonally reversing wind system, the Australasian monsoons. This has profound effects on the primary biological productivity in the upper layers. During southwest (summer) monsoons, which last from roughly June to September, strong, sustained winds from the southwest cause intense upwelling off the Arabian and Somali coasts, bringing up nutrients into the euphotic zone. This, in turn, causes a large increase in primary productivity. Consequently, summer monsoons give rise to rich fisheries as well as considerable carbon fixing. The former is important to fisheries management and the latter to the fate of anthropogenic carbon dioxide in the atmosphere (since biological productivity is an important pathway for sequestering carbon dioxide by the ocean). During northeast (winter) monsoons, winds reverse and blow from the northeast, causing upwelling off the Indian coast, but the chlorophyll concentrations off the Arabian coast decrease dramatically. This large seasonal modulation of primary productivity (and hence chlorophyll concentrations) in the Arabian Sea is also of significant interest to naval operations, principally due to corresponding modulation of optical extinction scales in the upper layers. Upwelling-induced structures such as filaments and eddies are also of importance.

The state of the upper ocean during southwest monsoons is of great importance to the agrarian societies on the Indian subcontinent. Monsoonal precipitation during summer, which in turn depends on the air-sea interactions in the Indian Ocean, is crucial to the welfare of nearly half the human population residing in the Indian and Chinese subcontinents.

Results

1. Physical Model

Accurate simulation of the physical state of the upper ocean is an important prerequisite to accurate prediction of its biological state, simply because the vertical advection plays a crucial role in the fate of nutrients in the euphotic zone. This in turn requires data-assimilative circulation models that make use of realistic surface forcing

and observational data constraints to maintain the state of the model ocean close to that of the real ocean. Prior to the enormously successful TOPEX/Poseidon (T/P) altimetric mission, it was impossible to routinely monitor the physical state of the upper ocean. T/P measures sea surface height (SSH) anomalies in the global oceans along pre-determined tracks at roughly 10 day repeat intervals, equatorward of roughly 66° latitude. SSH fluctuations are an indication of the variability of the geostrophic component of the surface currents and hence assimilation of these data is a strong constraint on ocean models. Along with realistic synoptic surface fluxes from accurate NWP models and assimilation of MCSST derived from AVHRR sensors on NOAA satellites, assimilation of T/P SSH anomalies provides a means of estimating the physical state of the upper ocean more accurately than hitherto possible. And this is the approach we have used in this study.

T/P mission, started in the autumn of 1992 and has provided excellent SSH anomaly data since roughly the beginning of 1993 to the present. These anomalies are directly related to the dynamic height anomalies caused by mesoscale variability in the upper ocean. Using statistical regression techniques, it is therefore possible to relate the T/P SSH anomalies to subsurface temperature/salinity anomalies, which can in turn be assimilated into the model. We have used EOF analyses of historical archives of CTD data in the North Indian Ocean to derive the relation between the dynamic height anomalies and the subsurface temperature anomalies. This relationship is then used to convert observed SSH anomalies along the sub-satellite tracks of T/P into pseudo-BT anomalies, which are then assimilated into the model using optimal interpolation (OI).

After spinning up the model with climatological forcing derived from historical archives of winds and other surface forcing, T/P SSH anomalies were assimilated into the model starting in 1993 (Lopez and Kantha, 2000 a and b). These hindcast runs were continued to the end of 1999. The surface forcing came from ECMWF (roughly 1 degree resolution) global daily weather prediction results archived at NCAR. However, since long simulations tend to amplify the forcing-induced biases, the SST was damped to 5-day composite MCSST to prevent the ML temperature from drifting too far from reality. This methodology provides the best means of realistic simulation of the oceanic state existing in a given region during a certain period, in the absence of extensive in-situ data.

Figure 1-3 show sample results. Figure 1 compares the currents at 30 m depth on May 30 and June 19, 1993. The high variability of currents resulting from the synoptic nature of surface forcing is evident. The Large Whirl off Somali coast and mesoscale features in the Arabian Sea and Bay of Bengal are clearly depicted. Most of this realism is due to synoptic forcing and altimetric SSH anomaly assimilation. Figure 2 contrasts the winter and summer monsoon periods. Figure 3 shows the time histories of mixed layer depth from stations in the middle of the Arabian Sea and the Bay of Bengal. Strong seasonal modulation, with twice-yearly peaks in ML depths, is evident in both regions, but the Arabian Sea ML is much deeper than that in the Bay of Bengal. This has to do with the fact that in the Arabian Sea, evaporation exceeds precipitation and the strong winds further deepen the ML. In contrast, large fresh water input into the Bay of Bengal from rivers draining the Indian subcontinent gives rise to shallower MLs.

Further results can be found in Lopez and Kantha (2000a, a copy of which is enclosed) and Lopez and Kantha (2000b). A website (www-ccar.colorado.edu/nio) contains the entire hindcast from 1993 to 1999. In addition Webster et al. (2000) discusses the possibility that the prolonged and severe flooding in Bangladesh during the summer monsoon of 1998 might have been due to anomalously high sea level in the Bay

of Bengal. Several additional manuscripts based on the 1993-99 hindcast, which is the most realistic model depiction of the North Indian Ocean during this period and which includes two ENSO events and the 1998 anomalous warming of the century, are planned.

2. Coupled Physical-Biological Model

It is traditional to develop models and test them thoroughly in 1-D mode, before converting them into a fully 3-D version. A typical example is the ML model of the upper ocean (Mellor and Yamada 1982, Kantha and Clayson 1994). In the same spirit, we undertook the development of the coupled physical-biological model of the upper ocean (Kantha 2000). The model incorporates knowledge gained in recent years from comprehensive programs such as Bermuda Atlantic Time Series (BATS) study carried out under JGOFS. The model is a general one-dimensional multi-component ecosystem model (GEM) that incorporates Kantha and Clayson (1994) upper ocean mixed layer model based on second moment closure of turbulence. The model is intended for incorporation into coupled physical-biochemical ocean models with potential applications to modeling and studying primary productivity and carbon cycling in regions such as the North Indian Ocean.

The model is nitrogen-based and the design is deliberately general enough to enable many of the existing ecosystem model formulations to be simulated and hence model-to-model comparisons rendered feasible. In its more general form (GEM10), the model solves for nitrate, ammonium, dissolved nitrogen, bacteria and two size categories of phytoplankton, zooplankton and detritus, in addition to solving for dissolved inorganic carbon and total alkalinity to enable estimation of the carbon dioxide flux at the air-sea interface. Dissolved oxygen is another prognostic variable enabling air-sea exchange of oxygen to be calculated. For potential applications to HNLC regions where productivity is constrained by the availability of a trace constituent such as iron or phosphate, the model carries the trace constituent as an additional prognostic variable. The modular design of the model enables subsets such as a 7-component N^3PZDB (GEM7), a 5-component N^2PZD (GEM5), a 4-component NPZD, and a 3-component NPZ model to be simulated, since a primary objective is to explore the minimum complexity needed to simulate the biogeochemical fate of the upper layers in a basin scale/global model for specific applications, such as studies related to primary productivity and upper ocean optical clarity, and carbon cycling.

Kantha (2000) presents 1-D model simulations for the Black Sea, Station PAPA and the BATS site. The Black Sea simulations assimilate seasonal monthly SST, SSS and surface chlorophyll, and the seasonal modulations compare favorably with earlier work. Station PAPA simulations for 1975 to 1977 with GEM5 assimilating observed SST and a plausible seasonal modulation of surface chlorophyll concentration also compare favorably with earlier work and the limited observations on nitrate and pCO_2 available. Finally, GEM5 simulations at BATS for 1985-1997 are consistent with the available time series. Kantha (2000) concludes that while it is generally desirable to employ a comprehensive ecosystem model with a large number of components, as is the prevailing practice when accurate depiction of the entire ecosystem is desirable, for basin scale/global applications, simpler formulations such as GEM5 may be necessary and perhaps sufficient in many simpler applications such as nowcasting and short term forecasting of the upper layer chlorophyll concentrations. This conclusion is mainly due

to the high sensitivity of ecosystem models to small changes in the parameterizations of various physical and biological processes, and the dearth of comprehensive and self-sufficient physical-biochemical observations (in spite of programs such as BATS) that introduces large uncertainties in physical and biological parameterizations, which increase directly with the model complexity, making fine-tuning of many parameters difficult, quite arbitrary and most often a mere modeling exercise. A simpler formulation such as GEM5 combined with assimilation of remotely-sensed SST and chlorophyll concentrations is more efficient and cost-effective for incorporation into three dimensional prediction models of primary productivity, upper ocean optical clarity and carbon cycling.

Figures 4 and 5 show the simplified versions of the general model, GEM7 and GEM5. The former accounts for dissolved nitrogen and bacteria, while the latter does not. Both assume single class size for phytoplankton, zooplankton and detritus, whereas the general version (GEM10, Figure 6) assumes two size classes. We will present only results from GEM5 for Station PAPA and the BATS site. For more details, the reader is referred to Kantha (2000). Figure 7 shows model simulations with GEM5 of pCO_2, the flux of CO_2 across the air-sea interface, dissolved inorganic carbon and oxygen, partial pressure of O_2 and flux of O_2 across the air-sea interface at Station PAPA for years 1975 to 1977. Observational data are also shown. Red curves show results without the influence of biology. Clearly, if the biological pathway is excluded, unrealistically high pCO_2 values and low pO_2 values would result. This shows the importance of accounting as accurately as possible for the biological pathway in studies of carbon dioxide sequestering by the global oceans, especially in regions such as the Arabian Sea, where entirely incorrect air-sea CO_2 flux results would be obtained if the primary productivity is not accurately simulated. Figure 8 shows simulations at the BATS site for years 1985 to 1997. The results are consistent with observations taken during this period. This is the one of the only two sites in the world where a continuous observational time series of physical and biological parameters are available for development and testing of ecosystem models.

Concluding Remarks

During this study, we have made considerable progress towards a realistic coupled physical-biological model of the North Indian Ocean. A data-assimilative physical model has been set up and tested in a hindcast mode for years 1993-1999. A 1-D physical-biological coupled model has also been set up and tested extensively with available observational data. The next step is to incorporate this into the 3-D physical model of the North Indian Ocean and test it with observations made in the Arabian Sea during 1994-96 (see Deep-Sea Research JGOFS Special Volumes on the Arabian Sea).

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Figure Captions

Figure 1. Ten day streak plots of the currents at 30 m depth from the data-assimilative model on 30 May and 19 June 1993. The use of synoptic winds allows the model to capture the high variability of the currents which exists during the southwest monsoon.

Figure 2. Ten day streak plots of the currents at 30 m depth from the data-assimilative model on 19 February and 18 August 1993. These snapshots capture the contrasting current systems of the northeast winter and southwest summer monsoon seasons.

Figure 3. Time histories of the mixed layer depth from a station in the central Arabian Sea and the central Bay of Bengal. The mixed layer at 15.5°N, 61.5°E in the Arabian Sea shows strong seasonal modulation with a deep mixed layer during the southwest monsoon and a shallow one during the northeast monsoon, while the seasonal modulation in mixed layer depth at 15°N, 90°E in the Bay of Bengal is much smaller.

Figure 4. Schematic diagram of possible biological pathways in GEM7, with a single phytoplankton, zooplankton and detritus size class.

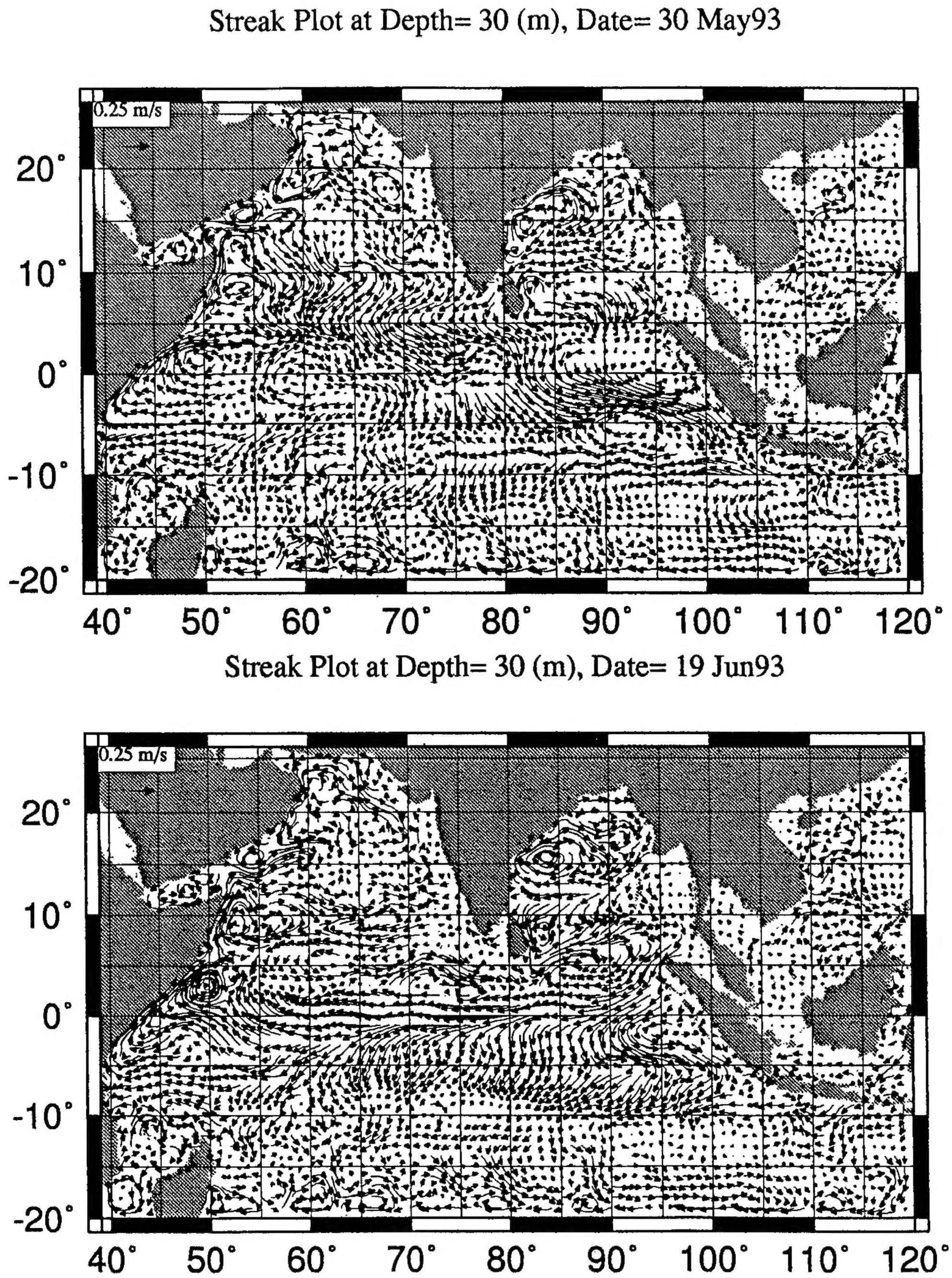
Figure 5. Schematic diagram of possible biological pathways in GEM5, a simplified model without bacteria or dissolved nitrogen.

Figure 6. Schematic diagram of possible biological pathways in GEM10, with two phytoplankton, zooplankton and detritus classes.

Figure 7. Model simulations of pCO_2 (μatm), flux of CO_2 across the air-sea interface ($\mu M\ m^{-2}\ s^{-1}$), dissolved inorganic carbon ($\mu M\ kg^{-1}$), dissolved oxygen ($\mu M\ kg^{-1}$), pO_2 (atm) and flux of O_2 across the air-sea interface ($\mu M\ m^{-2}\ s^{-1}$) from the beginning of 1975 to the

end of 1977. Observed SST has been assimilated into the model. The model values compare favorably with measured pCO_2 and dissolved oxygen concentration values shown by circles. Atmospheric pCO_2 and pO_2 values are also shown as well as the high pCO_2 and low pO_2 values resulting from removing the influence of biology. The dissolved inorganic carbon plot also shows the lesser drawdown resulting from ignoring biology. The dissolved oxygen plot also shows lower concentrations during summer resulting from ignoring biology.

Figure 8. Model simulations of surface pCO_2 (µatm), pO_2 (atm), the CO_2 and O_2 fluxes across the air-sea interface (µM m^{-2} s^{-1}), surface dissolved inorganic carbon and dissolved oxygen concentrations (µM kg^{-1}) from the beginning of 1985 to the end of 1997. The model SST and pCO_2 values compare favorably with measured values. Atmospheric pCO_2 and pO_2 values are also shown as well as the values resulting from removing the influence of biology.



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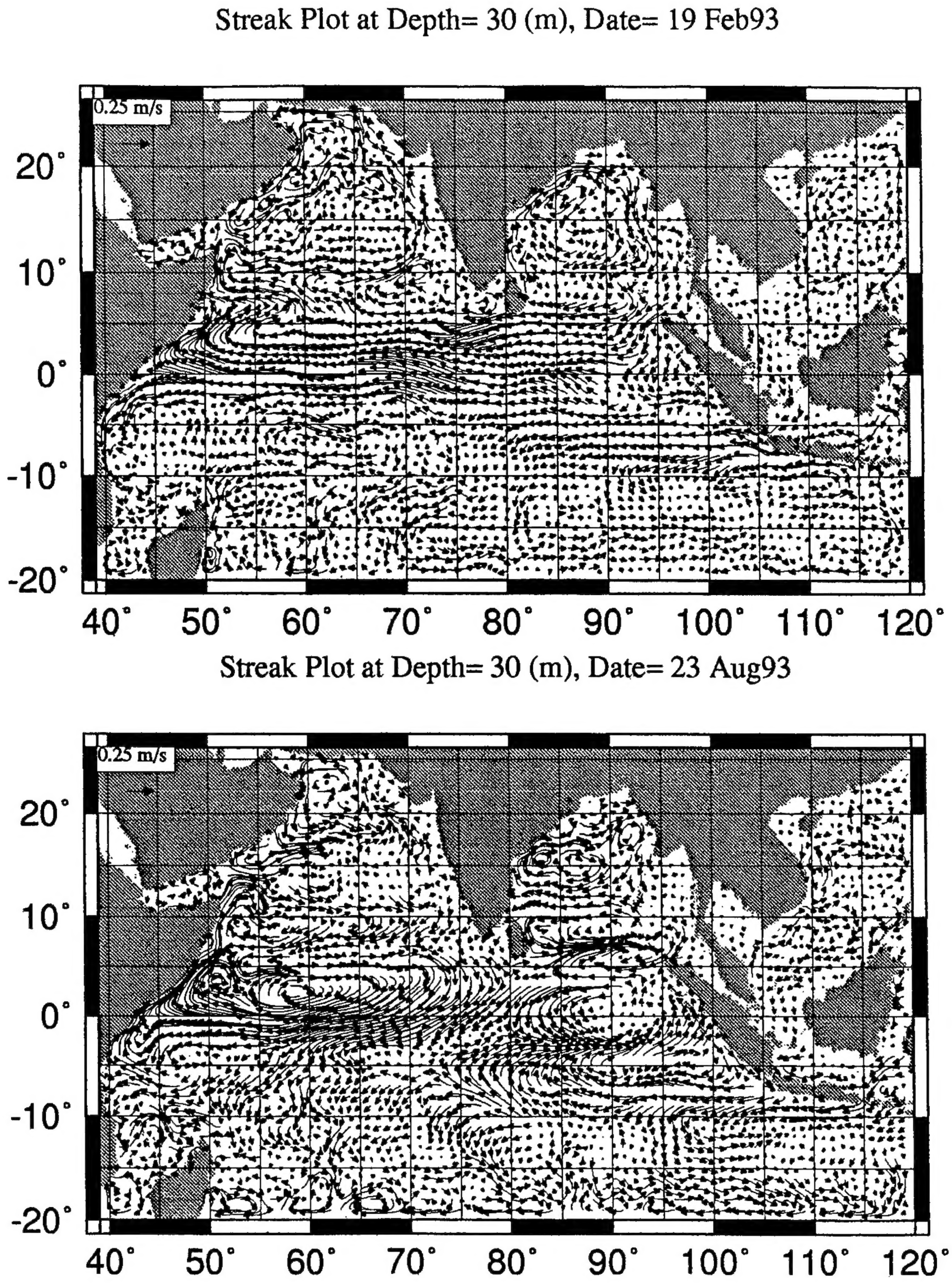

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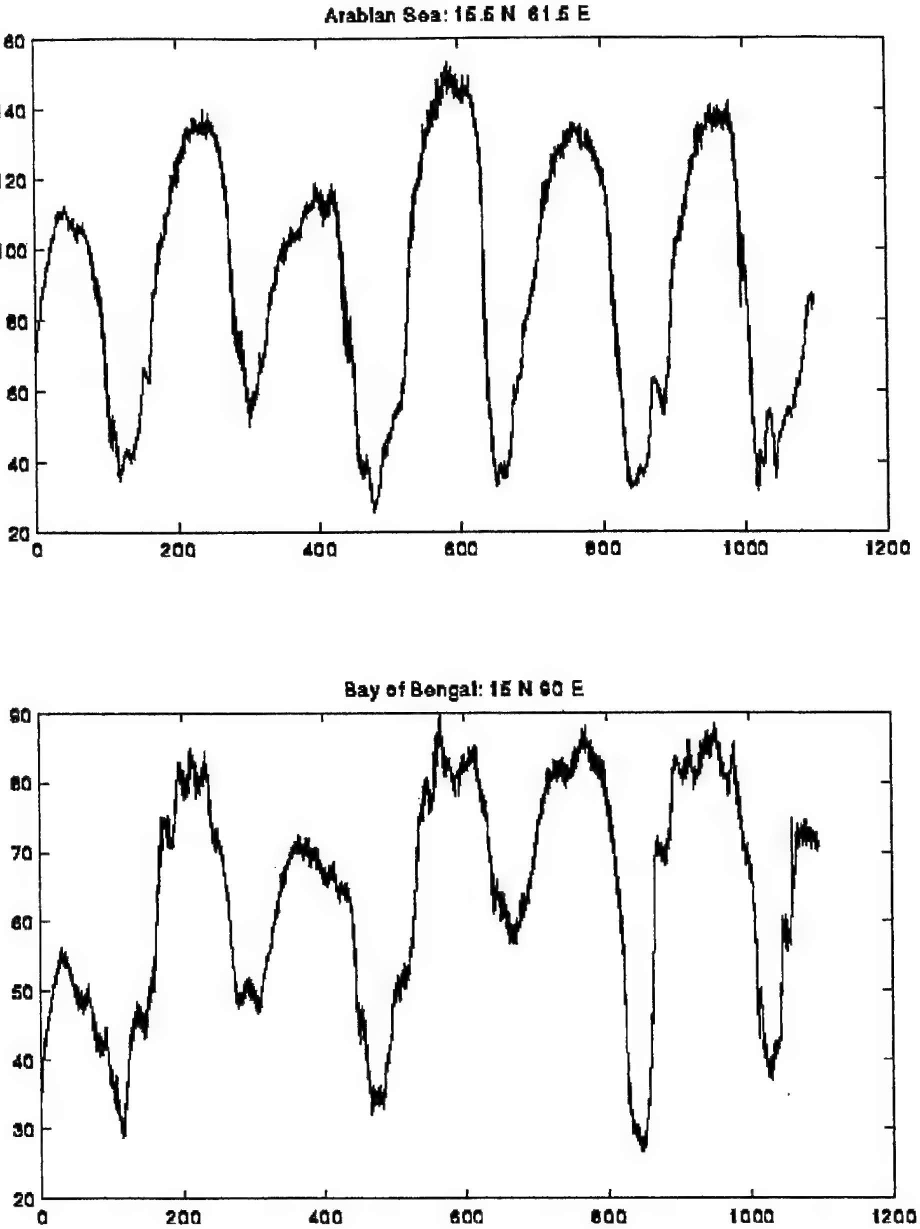

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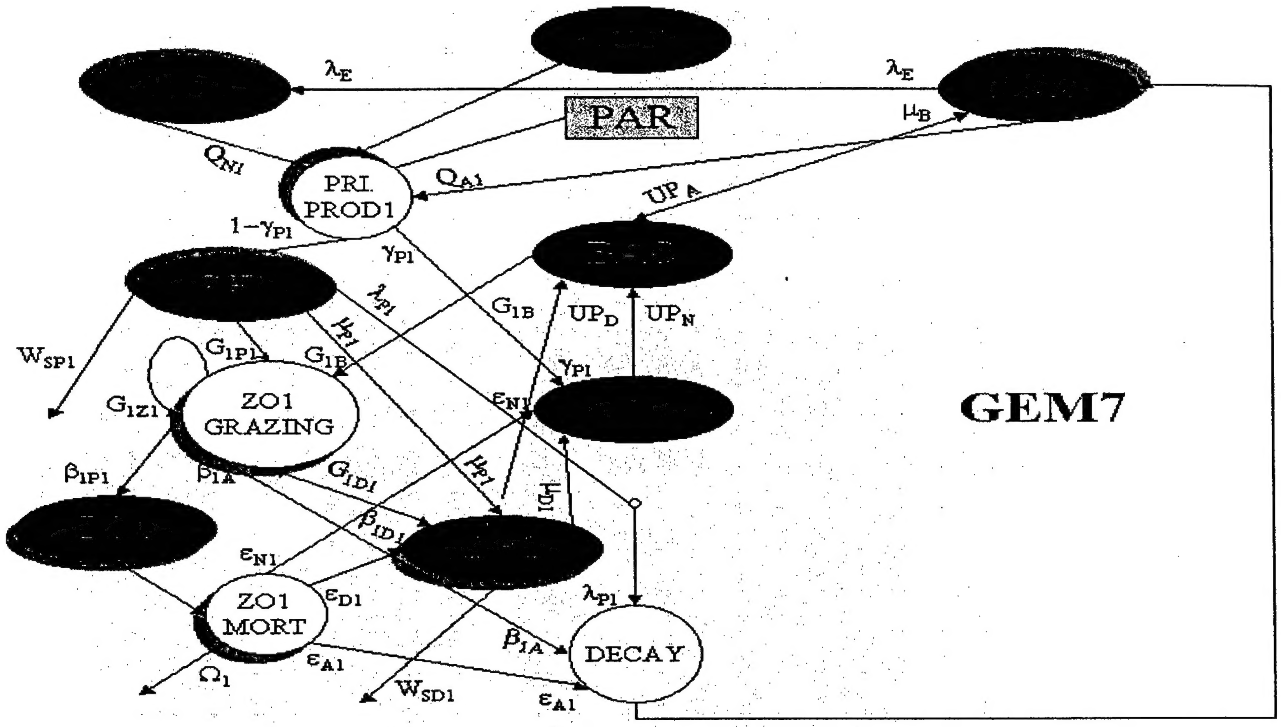


Figure 4. Schematic diagram of possible biological pathways in GEM7, with a single phytoplankton, zooplankton and detritus size class.

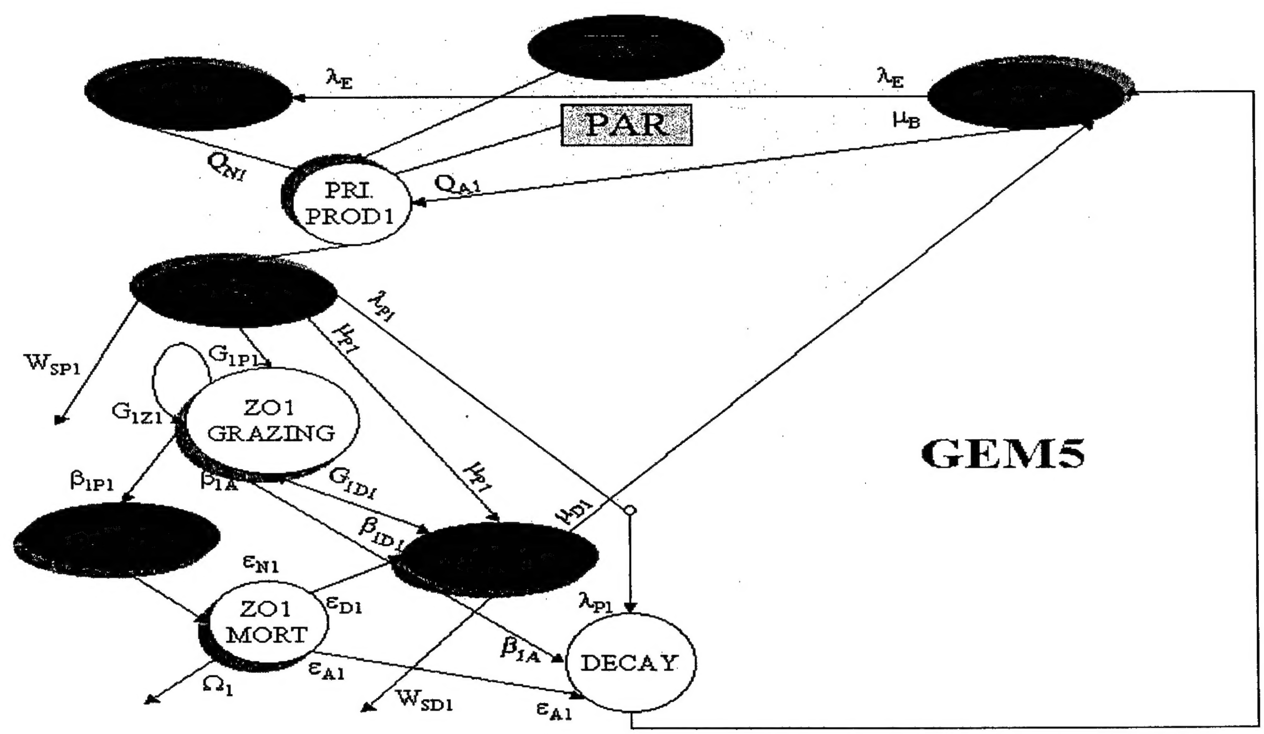
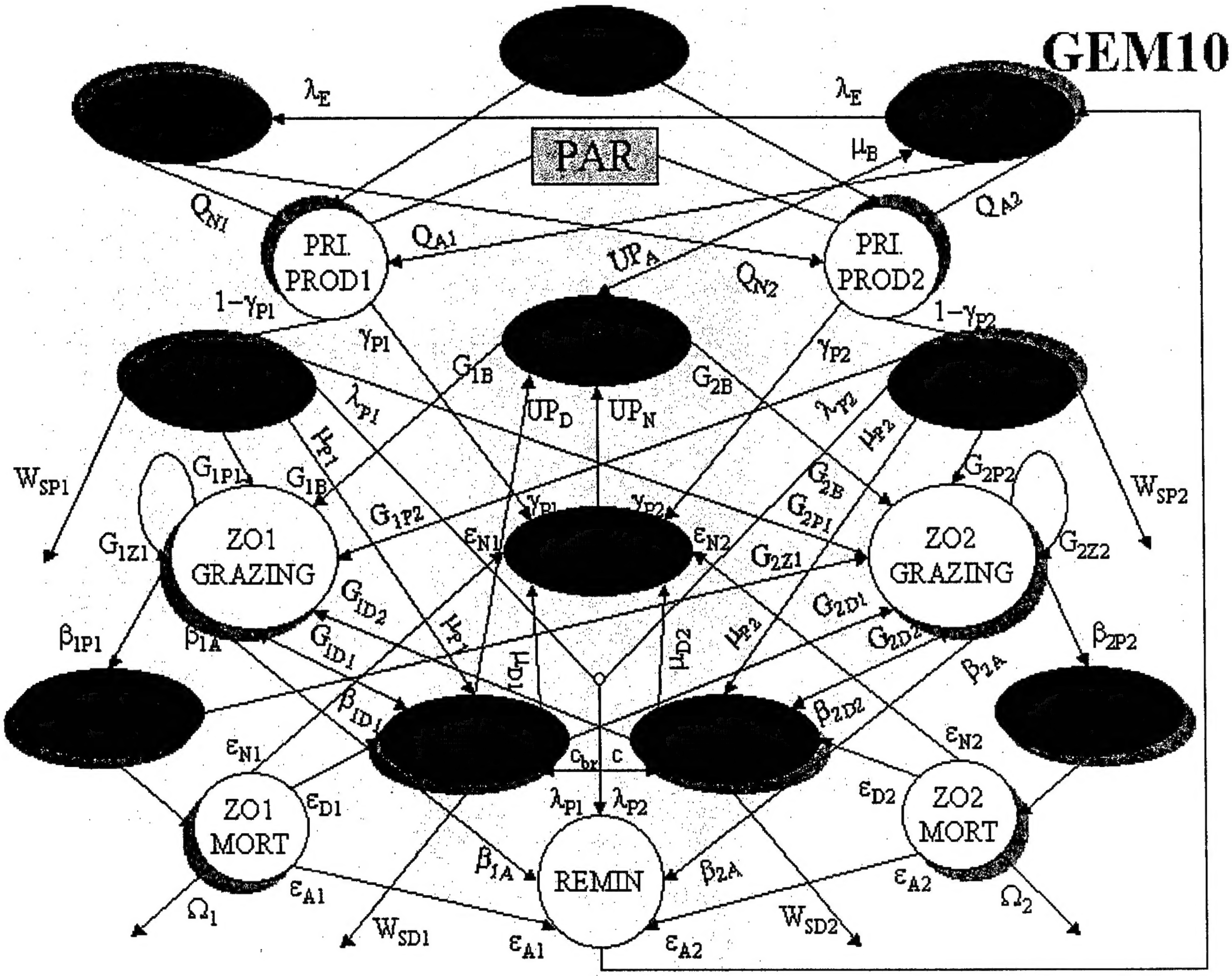


Figure 5. Schematic diagram of possible biological pathways in simplified model without bacteria or dissolved nitrogen, GEM5.



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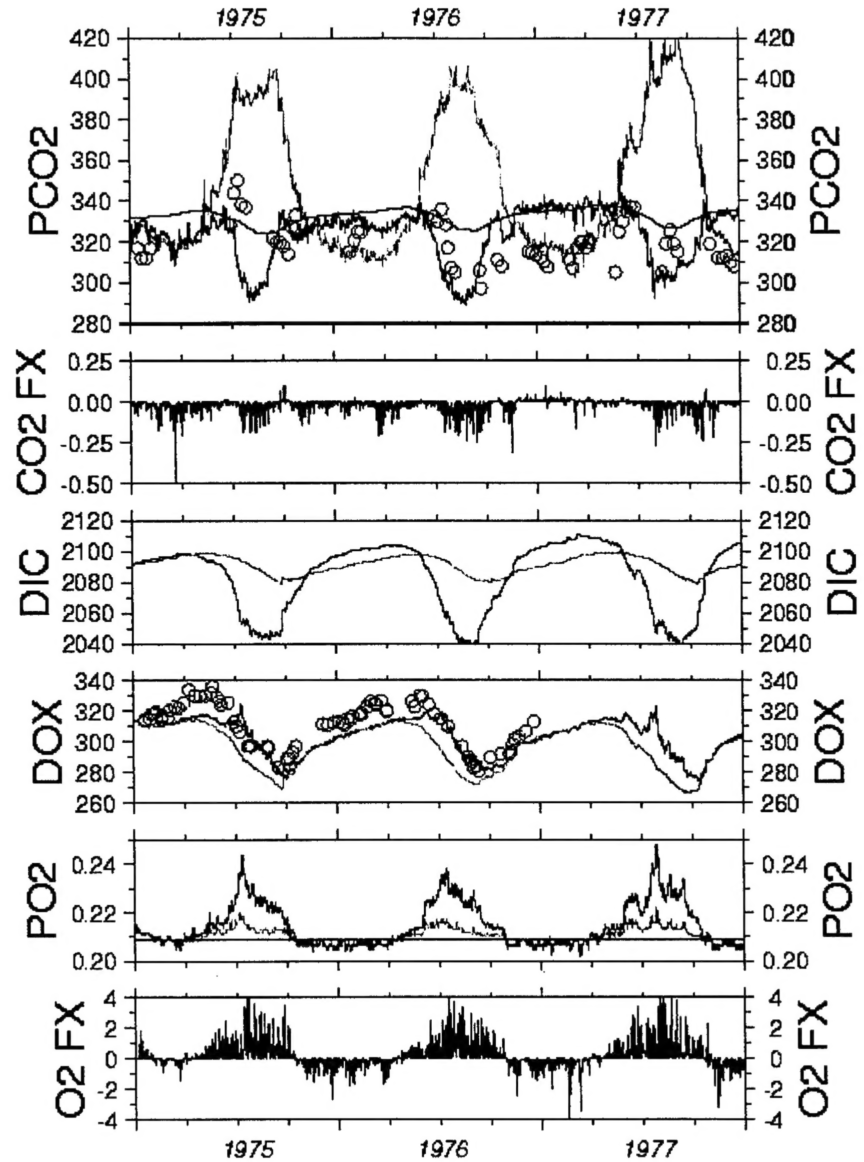

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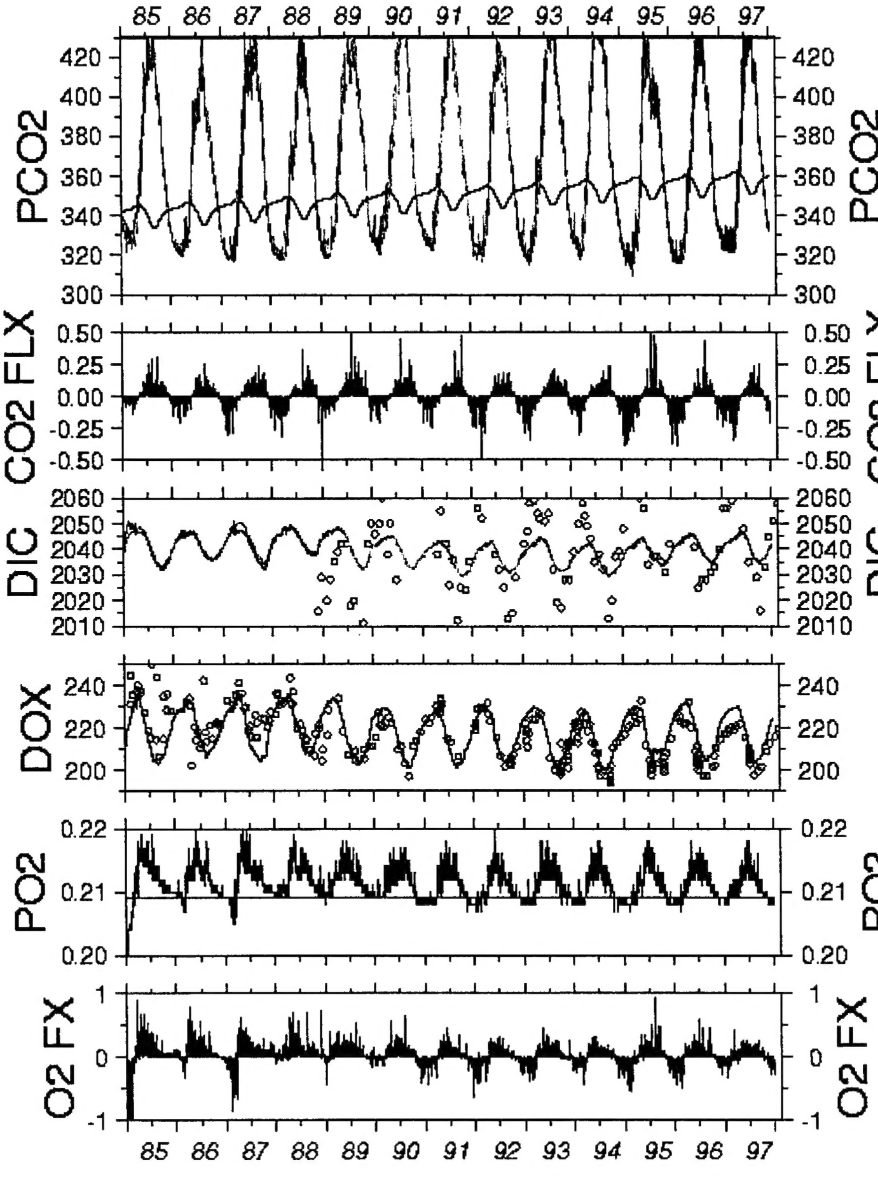

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